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GEOMORPHOLOGICAL CHARACTERISTICS OF SMALL DEBRIS FLOWS ON JUNIOR'S KOP, MARION ISLAND, MARITIME SUB - ANTARCTIC

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ABSTRACT

The geomorphological characteristics of small debris flows in a maritime sub-Antarctic environment are described. The morphological and sedimentological characteristics of the debris flows are comparable to debris flows documented for other parts of the world; their initiation appears closely linked to the unusual environment in which they are found. Sediment supply is generated by diurnal frost heave of loamy sediment associated with *Azorella selago*. The debris flows are triggered by sediment mobilization upon saturation of the frost-heaved surface gravel and overland flow over the low-permeability and frost-susceptible slope materials. Morphological effects of the flows are short-lived due to obliteration by subsequent frost heave activity. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: debris flows; sedimentology; debris flow initiation; maritime sub-Antarctic

INTRODUCTION

Debris flows have been reported and described morphologically and sedimentologically for a wide variety of environments (e.g. Innes, 1983; Nieuwenhuizen and Van Steijn, 1990; Harris and Gustafson, 1993; Boelhouwers *et al.*, 1998). Prerequisites for their occurrence appear to be steep slopes close to the angle of repose, availability of material subject to mobilization and sufficient moisture to saturate and mobilize the debris (Innes, 1983). Triggering normally takes place by increased pore pressure due to high-intensity rainfall events or rapid snowmelt with subsequent saturation and failure of slope materials (Johnson and Rahn, 1970). An alternative model has been described by Takahashi (1980) explaining sediment mobilization in channels when a certain head of water appears at the surface of saturated debris. Blijenberg (1998) describes debris flow initiation by overland flow induced by short-duration, high-intensity thunderstorms in the French Alps.

As part of ongoing research on slope dynamics in the maritime sub-Antarctic environment of Marion Island, debris flows were noted on moderately steep slopes of some scoria cones. As no previous records of debris flows were found for the islands in the Southern Ocean, a morphological and sedimentological analysis is presented and a model for their initiation proposed.

THE STUDY AREA

Marion Island (46°54′S, 32°45′E) is located in the South Indian Ocean and is one of two islands, which together constitute the Prince Edward Island Group (Figure 1). The island has an area of approximately 290 km^2 and rises to 1230 m a.s.l. Situated just north of the Antarctic Polar Convergence, the exceptionally maritime climate is characterized by low temperatures throughout the year and a small diurnal and seasonal temperature range. Summer mean maximum and minimum temperatures are 10·9°C and 5·2°C, and the

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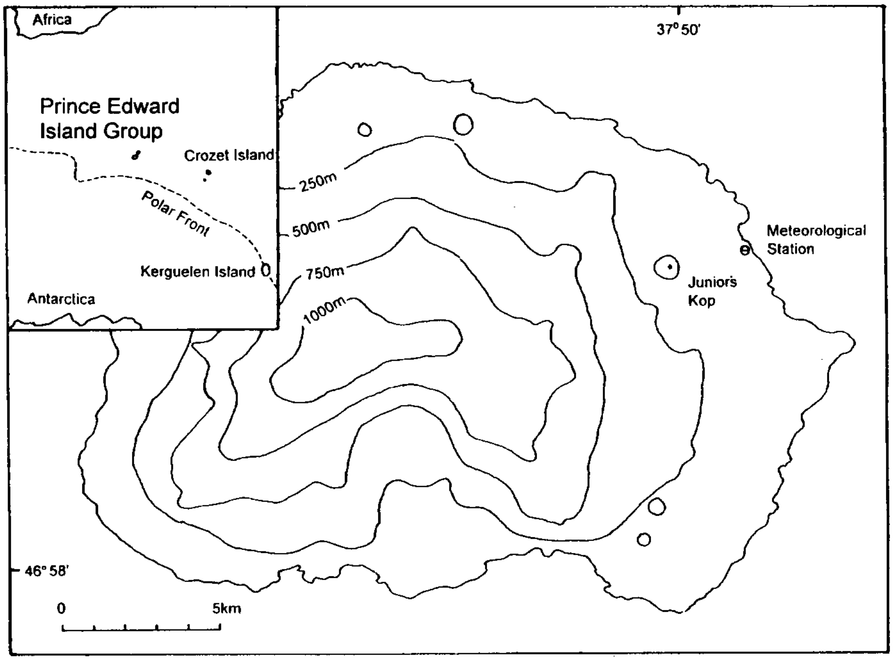

Figure 1. Location of Junior's Kop and position of the Prince Edward Island Group

winter means are 6·6°C and 1·6°C, respectively, based on the 1960–1997 record at the Meteorological Station (24 m a.s.l.) (S. Holness, unpublished data). On average, precipitation occurs on 25·6 days of each month, with a mean annual total of 2332 mm. Winds blow most frequently from the northwest, with an average velocity of 32 km h^{-1} (Schulze, 1971). The frost environment at the coast is characterized by diurnal frost cycles, which occur on average on 112 days per year (S. Holness, unpublished data). Experimental and field evidence shows present-day frost heave to be restricted to the upper 5–10 cm of the surface. Needle-ice appears to be the dominant form of segregation ice and is frequently observed.

Geologically, the island comprises the peak of a shield volcano. Verwoerd (1971) dated an older sequence of grey basaltic lavas to 276 ka BP, which in most places is overlain by black lavas and scoria, the most recent of which has been dated to 10 ka BP (Verwoerd, 1990). Hall (1978) identified three glacial periods on the island, the most recent of which lasted from 70 ka BP to 11 ka BP.

This study took place on Junior's Kop, a prominent scoria cone approximately 2 km inland from the Meteorological Station (Figure 1). The cone consists mostly of cohesionless, highly permeable scoria material. However, there are some welded layers below the crater summit. The cone rises to a height of 306 m a.s.l. The study took place on the southeast side of the cone at an altitude of about 200 m a.s.l.

MORPHOLOGY

Several debris flow tracks were found on the southeast slope of Junior's Kop. Here, a shallow depression, 10–20 m wide, extends for some 200 m up the slope (Figure 2). Although the depression is below the vegetation limit its surface is bare, with *Azorella selago* dominating the surrounding slopes. The macro-slope profile is rectilinear at an angle of 22–24°, but more irregular at a larger scale. The bare surface of the depression consists of a thin gravel layer 1–3 cm thick beneath which a heterogenous mixture of gravel and loam is found. Several small debris flows were found on these slopes, two of which are described here in more detail.

The general characteristics of the two debris flows are outlined in Figure 3, referred to as upper flow and lower flow according to their slope position. Both flows are found in similar topographic locations. The

Figure 2. View of the elongated depression on the southeast slopes of Junior's Kop showing several small debris flow tracks (photograph taken 13 May 1997)

source areas take the shape of small catchments that end characteristically with the transport zone followed by a final deposition zone. Each of these units is described separately.

The source area

The source areas of the flows take the shape of shallow, localized basins on a 23° slope. They have a length of about 12–15 m and are several metres wide. Continuous *Azorella selago* cushions form the western boundary of the small catchment shaped area (Figure 3). The bare sediment consists of a cohesionless, surficial gravel layer *c*. 1–2 cm thick beneath which gravel is contained in a clay–loam matrix. Within the basins, areas of several square metres have been stripped of surface gravel. This indicates removal of this loose, cohesionless material by sheetflow. No scouring of the loamy sub-surface was noted, except where flow starts concentrating, such as near individual *Azorella* cushions. Concentration of sheetflow can be seen to start after some metres. In the case of the upper debris flow this occurred against the *Azorella* cushions. It is here that surface runoff initiates rill development.

The transport zone

Both debris flows have essentially straight channels except where obstructed by *Azorella* cushions (Figure 3). Total length of the transport zone is 30 m and 37 m for the upper and lower flow, respectively, on a slope of about 22–24°. In the case of the upper flow channel, evidence for debris flow dynamics only appears after 11 m in the form of a small end-lobe of a debris flow pulse (Figure 3a). The lobe is dissected by subsequent flow through the channel. Another set of end-lobes produced by small pulses during the early phases of the flow event is found at 16 m. Similarly, in the lower flow channel two dissected lobes of small earlier flow pulses, or events, are found at about 11 m and 24 m from the start of the channel.

Levees occur along virtually the entire length of the transport zone of the lower flow (Figure 3b). They form continuous, narrow ridges rising 2–6 cm above the surrounding slope on both sides of the channel. No

(a)

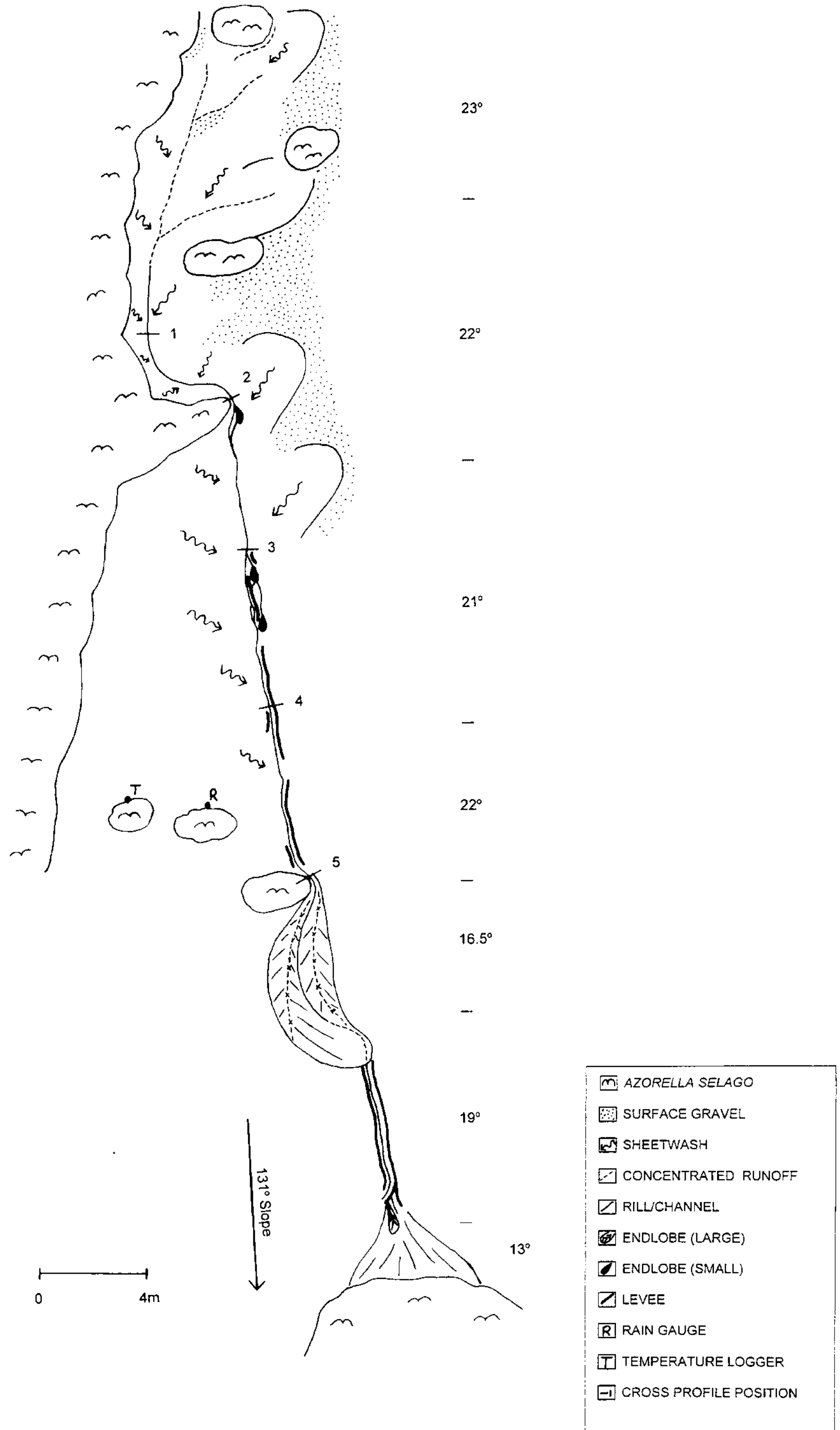

Figure 3. Sketches of the two debris flows described: (a) upper flow; (b) lower flow

(b)

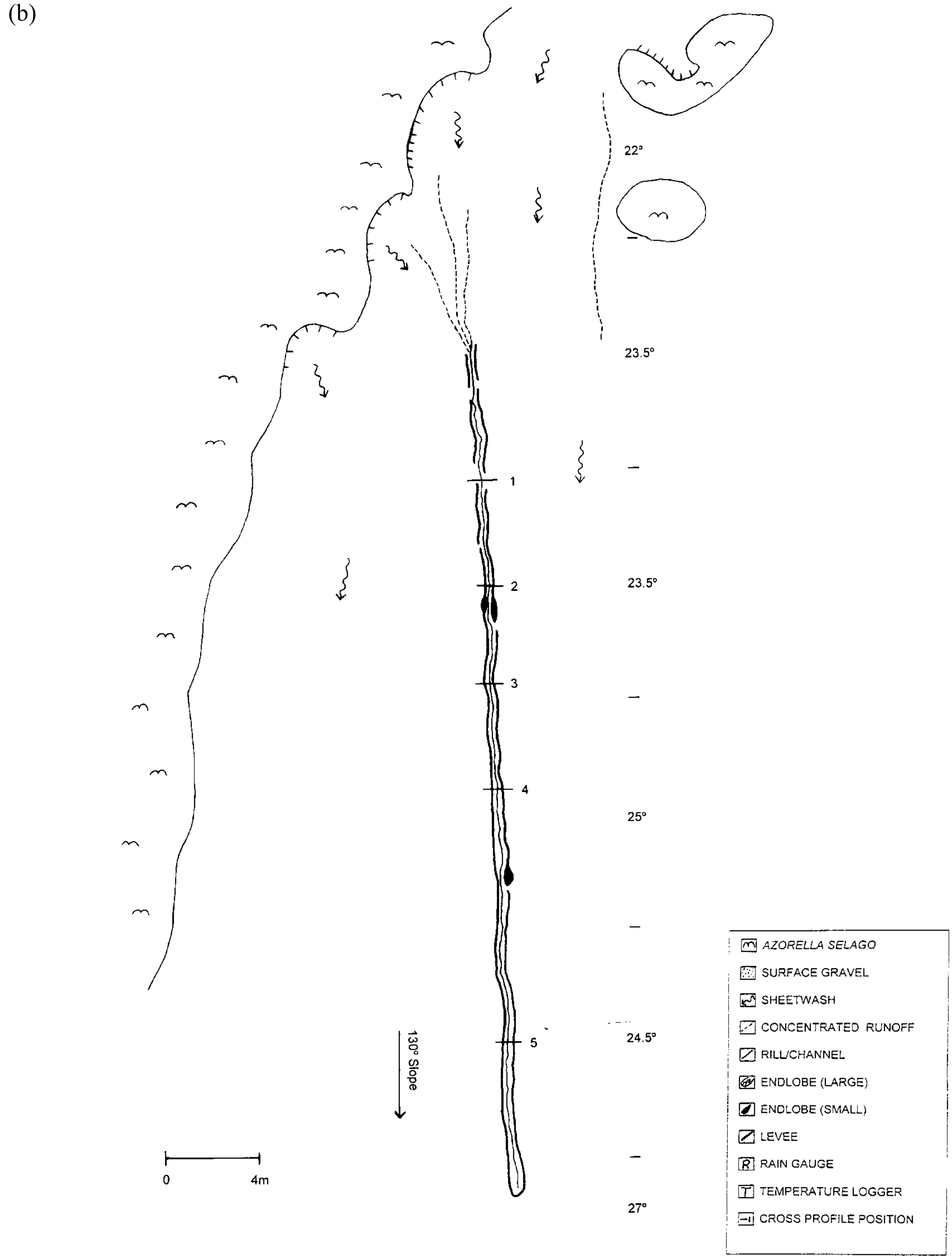

Figure 3 (continued).

(a)

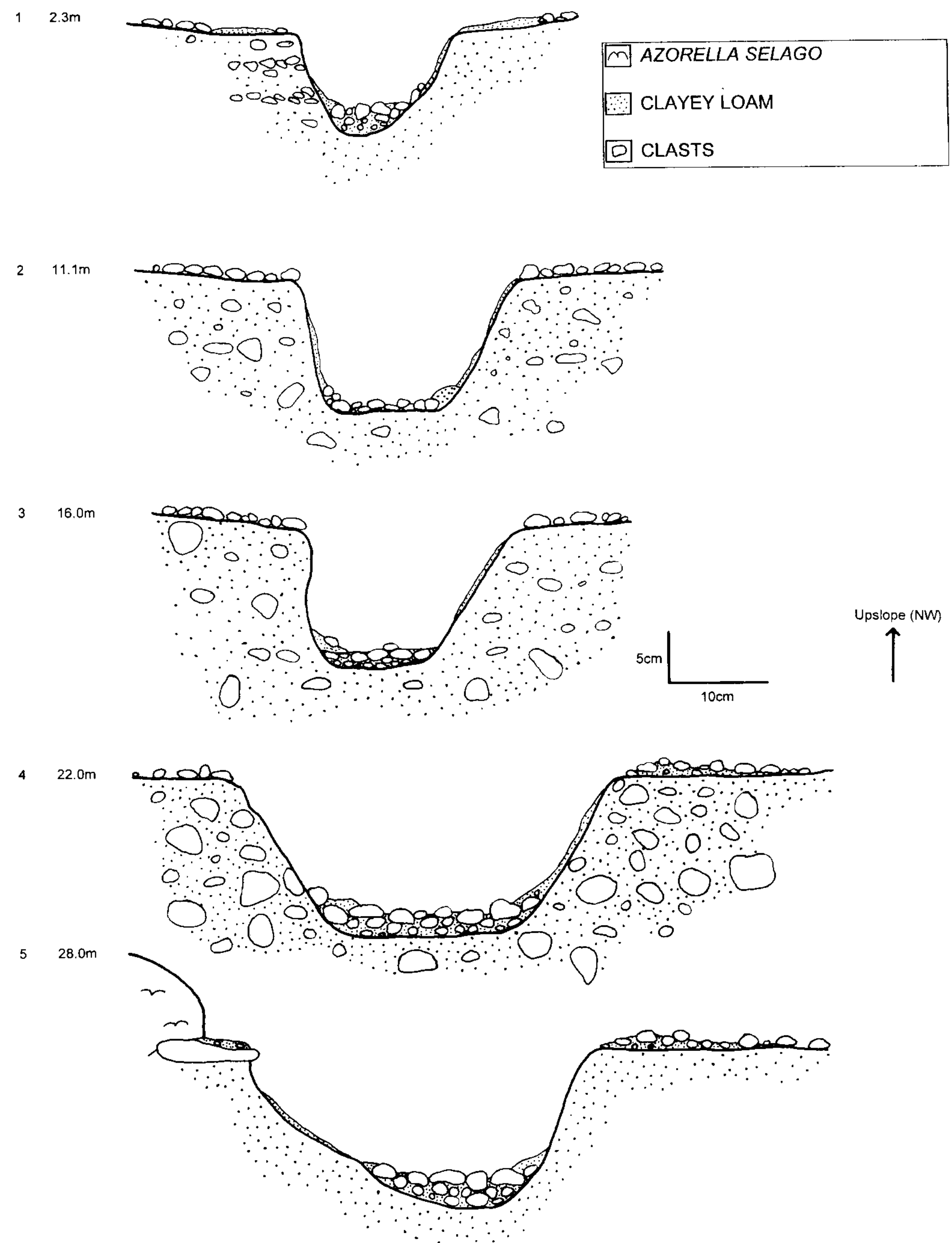

Figure 4. Channel cross-profiles of (a) the upper flow, and (b) the lower flow

(b)

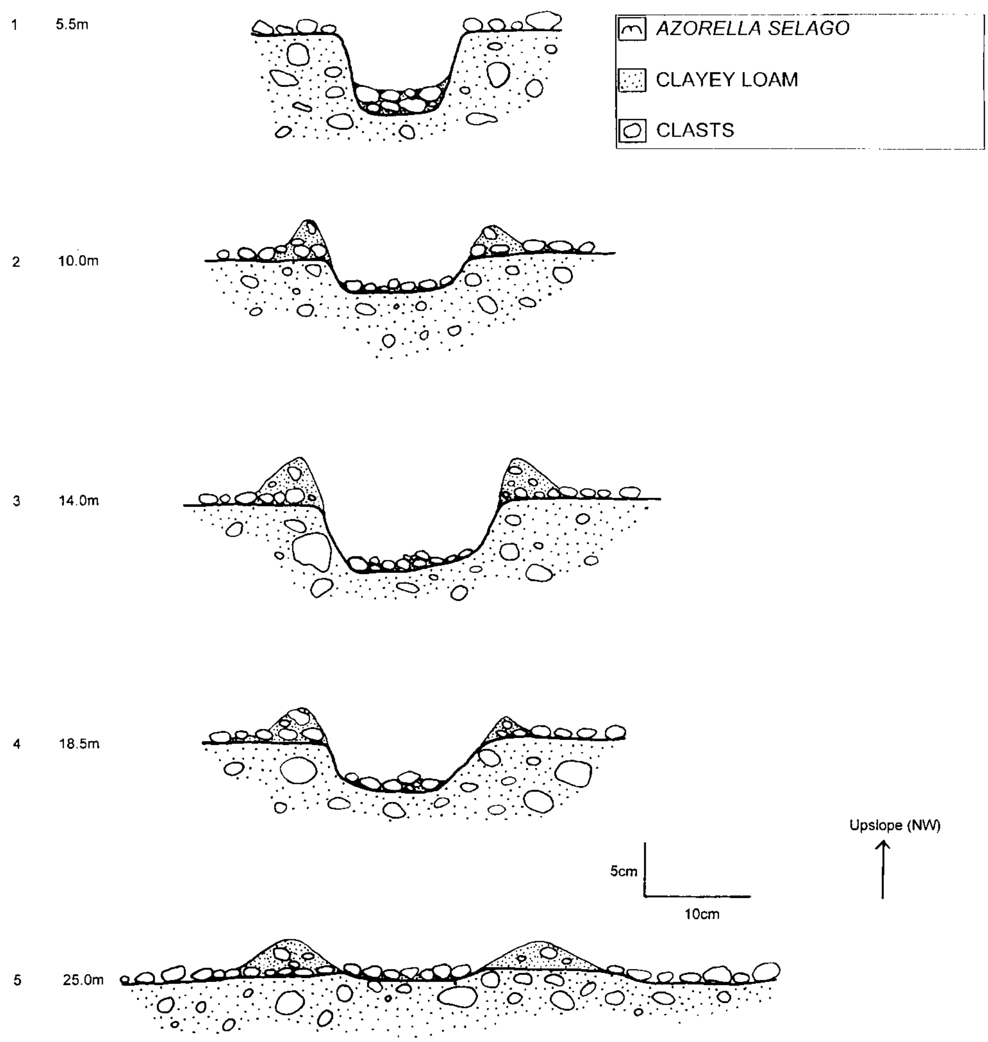

Figure 4 (continued).

trends in levee size could be noted along the length of the track. The inner levee sides have steep walls descending directly into the flow channel. The slope of the outer levee is generally more gentle, but may be very steep ending with an abrupt boundary on surrounding slope material. The contact of the levee with the slope is entirely depositional with no disturbance noted of the surface gravel layer beneath the levee deposit. Matrix from the flow has generally penetrated into the voids between this gravel. Levee development for the upper flow is very poor and starts only after 16 m from the start of the channel. Levees are only found on the east side of the channel. Their absence on the west flank can be related to the extensive signs of sheetwash on that side of the slope. Any levees would have been removed either during or following their deposition by surface runoff entering the channel.

Channel morphology of the two flows appears similar in that both are characterized by flat floors and steep walls (Figure 4). However, some important differences are worth noting. The top cross-section of the upper flow shows a V-shaped profile where the channels show no signs of debris flow behaviour (Figure 4a). It

appears that at that point the channel developed by fluvial incision rather than debris flow dynamics and closely resembles the rills in the source area. The poorly developed levees and the end-lobes found lower down along the channel clearly suggest a change in flow dynamics. This is reflected in the change to a flat-floored channel shape. The lower flow shows a similar flat-floored channel along the entire length of the flow track (Figure 4b). Both channels are incised in the slope indicating active scouring of the flow, creating its own channel. Depth of scour is higher for the upper flow. A general increase in channel size in the downslope direction also suggests an increased erosive capacity of the flow in that direction. In contrast, the lower flow channel obtains a fairly constant size with a tendency for the channel to flatten out somewhat in the downslope direction. This is most clear in the lowest 10 m of the channel where the flow does not erode but, rather, loses mass by depositing levees and gully floor material.

Deposition zone

Several small end-lobes of debris flow pulses are found along the channels of both debris flows (Figure 3). The upper flow further terminates in two main end-lobes some 3 m long and 1 m wide. The location of both coincides with a local reduction in slope angle. This has undoubtedly resulted in a reduction in momentum of the flow, triggering deposition of its sediments. The lower flow shows no signs of an end-lobe. This can be understood considering the fact that it lost much of its mass over the lower 10 m in the form of levee deposition. With no new material being incorporated in the flow by channel scour, the flow terminated by losing its mass until it depleted itself.

SEDIMENTOLOGY

Particle size and sorting of the sediment was established from samples taken at both debris flows. Slope material was sampled from the loose surface cover and at 5 cm depth in the source area and adjacent to sample sites along the transport zone. Material from the right and left levees and channel floor was sampled at three sites along the transport zone. For the upper flow, samples were taken at transect sites 2, 4 and 5 and for the lower flow, at transects 1, 3 and 5 (Figure 3). End-lobe samples were obtained only from the upper flow. All samples were oven dried and sieved on regular phi unit sieves from less than $-4\ \phi$ (> 16 mm) to $4\ \phi$ (0·063 mm). The low proportion of fines precluded a meaningful division into silt and clay proportions. Mean particle size and sorting values were calculated according to the procedures outlined in Briggs (1997). Results are summarized in Table I and Figure 5.

The surface of the depression in which the debris flows are found consists of over 50 per cent gravel with low percentages of smaller fractions. The dense loam found beneath the loose surface material may be associated with the growth of *Azorella selago*. The variation in composition of both the surface and sub-surface slope material is very small over the entire debris flow trajectories. This implies that any changes in composition of the debris flow deposits are due to the transport and deposition mechanisms involved.

The cumulative grain-size distribution curves for the channel floor, levee and end-lobe deposits are very similar to those of the surficial gravel cover, with values and trends being remarkably similar for both debris flows described. It can be assumed that the bulk of the debris flow deposits is derived from the cohesionless surface gravel. The smaller fraction incorporated into the flow by channel incision into the more cohesive, loamy sub-surface material, has only a small effect on the material composition of the flow deposits. This is most noticeable in the end-lobe and levee deposits, which contain a lower gravel and higher sand fraction than the surface material. The higher sand fraction in the end-lobe deposits, compared with the levee material for the upper flow, suggests a reduced flow competence possibly as a function of the downslope reduction in slope angle. On the other hand, the channel floor deposits have the highest gravel content of all material due to removal of the finer fractions. Sediment characteristics are in close agreement with expected variations in flow competence due to lateral and downslope velocity variations.

Sorting of both the slope material and debris flow deposits is poor to very poor, with the exception of the upper section of the channel floor (Table 1). This suggests generally high viscosity flows with transport insufficient to distribute material proportionally towards the levees. No lateral or vertical sorting could be

Table I. Mean phi and sorting values for the upper flow sediments and the lower flow sediments (vp = very poorly sorted; p = poorly sorted; m = moderately sorted; as defined by Briggs, 1977)

	Surface material	Sub-surface material	Left levee	Right levee	Gully	End-lobe
Upper flow						
Source						
mean phi	−2·28	0·25	n/a	n/a	n/a	n/a
sorting	2·30 (vp)	2·08 (vp)				
Upper						
mean phi	−2·92	0·78	n/a	n/a	−3·08	n/a
sorting	1·50 (p)	1·78 (p)			1·00 (m)	
Middle						
mean phi	−2·52	−0·67	−2·60	−1·87	−2·73	n/a
sorting	1·45 (p)	2·20 (vp)	2·80 (vp)	2·52 (vp)	2·25 (vp)	
Lower						
mean phi	−2·38	−0·98	−2·45	−3·03	−2·80	n/a
sorting	1·95 (p)	2·28 (vp)	1·75 (p)	2·00 (p)	1·98 (p)	
End-lobe						
mean phi	n/a	n/a	n/a	n/a	n/a	−1·78
sorting						2·18 (vp)
Lower flow						
Source						
mean phi	−2·03	0·03	n/a	n/a	n/a	n/a
sorting	2·05 (vp)	2·28 (vp)				
Upper						
mean phi	−2·98	0·40	−1·62	−2·38	−3·37	n/a
sorting	1·25 (p)	1·98 (p)	3·00 (vp)	2·35 (vp)	0·98 (m)	
Middle						
mean phi	−2·97	0·03	−1·55	−2·55	−2·78	n/a
sorting	1·10 (p)	2·50 (vp)	2·65 (vp)	2·25 (vp)	1·70 (p)	
Lower						
mean phi	−2·82	−0·33	−2·55	−1·80	−2·77	n/a
sorting	1·30 (p)	2·53 (vp)	2·30 (vp)	2·58 (vp)	1·35 (p)	
End-lobe						
mean phi	n/a	n/a	n/a	n/a	n/a	n/a
sorting						

visually detected within the levees. The decrease in sorting of deposits down both channels suggests an increase in viscosity (sediment content) in the downslope direction during the flow event.

NEEDLE-ICE ACTIVITY

Field observations indicate that needle-ice-induced processes play an important role on the investigated slope. Widespread needle-ice growth was found two days after the initial survey of the flows, lifting the entire slope surface. Collapse of the ice needles actively destroyed the debris flow channel walls, levees and end-lobes, thus rapidly obliterating its effects on slope micro-topography (Figure 6). The channel floor material proved too coarse for needle-ice growth. Besides its general smoothing effect on the slope morphology, needle-ice-induced frost heave was found to generate a new, friable surface layer of sediment in the area stripped of surface gravels by overland flow. Needle-ice activity thus appears to play an important role in making available source material for transport by overland flow. The heaved surface layer has been shown to be depleted in fines (Table 1). Initial removal of the finer sediment fractions of the heaved material may be accomplished by wind, splash or surface runoff. Mobilization of the remaining cohesionless surface gravel is readily generated in response to high-intensity rainfall events or during snowmelt. With the high annual number of diurnal frost cycles sediment production rates are very high. The abundance of sediment in the source area is one of the main prerequisites for the initiation of debris flows by surface runoff.

(a)

(b)

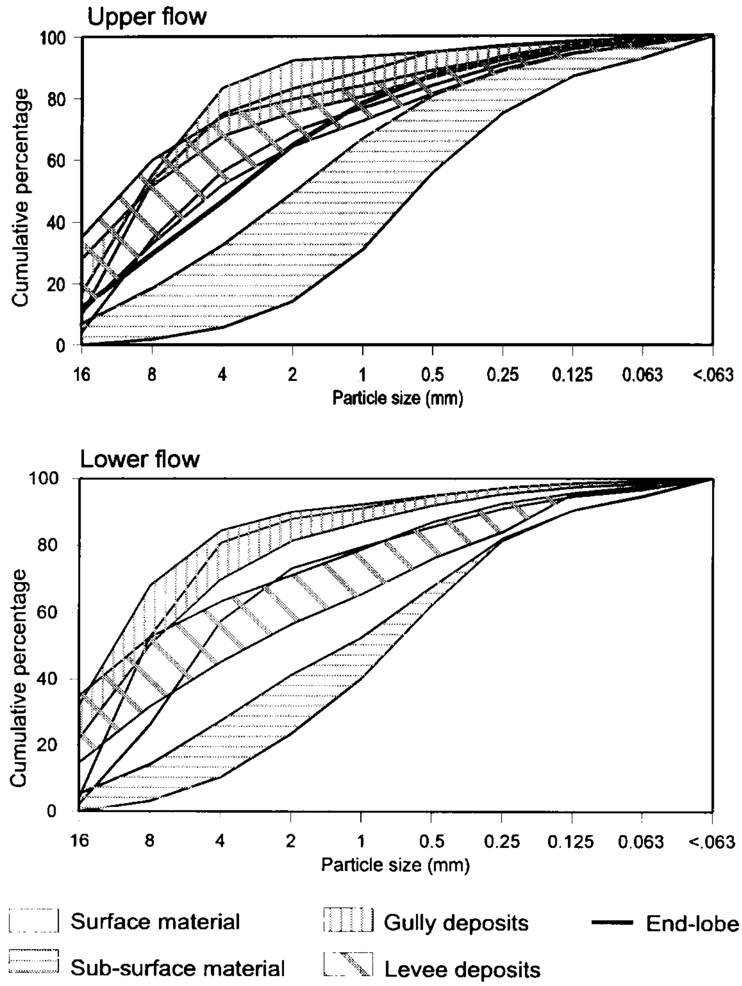

Figure 5. Envelopes for cumulative grain size distributions for (a) upper flow sediments and adjacent slope material, and (b) lower flow sediments and adjacent slope material

DISCUSSION

Field observations on other parts of the island show that debris flows are mostly concentrated on relatively steep slopes with sparse or no vegetation underlain by the loams associated with *Azorella selago*. This is significant as this loam greatly reduces permeability and, in turn, favours conditions for infiltration-excess overland flow capable of transporting the surface gravel layer. Downslope concentration of the sheetflow generates rill development as indicated by the upper-channel cross-sections. High sediment load concentrations, however, lead to increased viscosity and development of true debris flow dynamics. Considering the high annual number of precipitation days this process is expected to be very common, but may go largely undetected due to rapid obliteration of its effects by diurnal frost heave processes.

The observations presented here point at the importance of frost heaving in terms of material preparation for subsequent mobilization. Frost-heaved material is known to lose much of its cohesion and lower its bulk density (Williams and Smith, 1989). Both these effects aid debris flow initiation by reducing internal

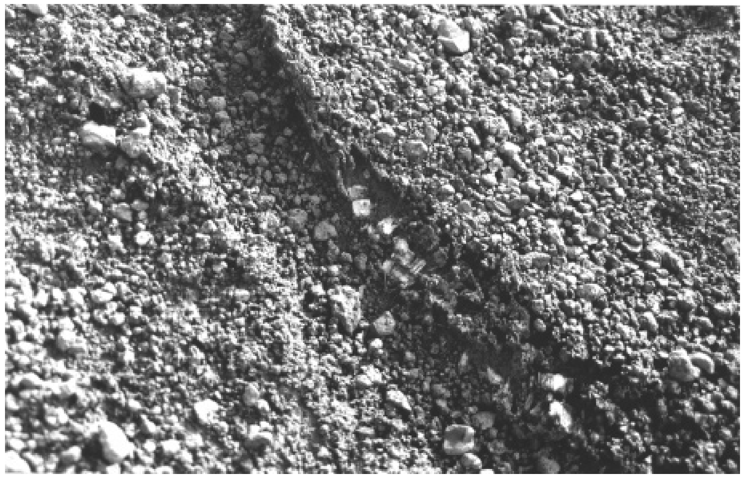

Figure 6. Needle-ice growth in the debris flow channel, levees and slope material, actively destroying the micro-relief generated by the flow and redistributing its sediments

resistance of the material and increasing infiltration rates, respectively. The loam-rich, frost-susceptible parent material has low permeability characteristics resulting in rapid build-up of pore pressure in the surface gravel layer and generation of saturation overland flow. This effectively leads to conditions described by the initiation model of Takahashi (1980) whereby mass flow is generated upon saturation of the debris with a water film present at the surface. Blijenberg (1993) describes similar triggering of micro-scale mass movements in response to rainfall simulations using high rainfall intensities on steep slopes. In this case a cohesionless surface layer is prepared by the swelling behaviour and rapid softening of lime-cemented black marl debris upon rainfall.

CONCLUSIONS

The debris flows described for this maritime sub-Antarctic environment are, besides their small size, very similar in morphology and sedimentology to those described for many other parts of the world. However, the model proposed here for debris flow initiation relies on a specific combination of material and climatic controls. The debris flows described are found on frost-susceptible materials with low permeability on moderately steep slopes. A high frequency of diurnal frost cycles results in effective material preparation for subsequent transport by needle-ice-induced frost heave. This is accompanied by frequent precipitation allowing for the generation of overland flow to mobilize the frost-heaved surface material and generate the debris flows as described in the Takahashi (1980) model.

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